Distinguishing quantum erasure from non-local interference

Ghenadie N. Mardari
*Rutgers University, New Brunswick, NJ 08901**
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Chaotic beams, generated via spontaneous parametric down conversion, do not always generate first-order interference. However, fringes can be observed in the coincidence count regime, when associated entangled beams are properly measured in separate contexts. This phenomenon can be interpreted either in terms of quantum erasure (recovered first-order interference), or in terms of non-local interference (fourth-order effects in superposition). The two explanations lead to different predictions for a specific context, which is described in the text.

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Spontaneous parametric down-conversion is a remarkable source of entangled photon pairs. It has been used with great success for the investigation of correlated beams, usually identified as *signal* and *idler*. At the same time, each of these beams has independent properties that are interesting on their own. For example, it has been shown that signal (or idler) beams do not easily generate first-order interference in a Young interferometer, in the singles count regime [1, 2]. This has been plausibly explained in terms of the divergence of these chaotic beams [2], and also in terms of their lack of spatio-temporal coherence [1]. It is also well established that certain types of coincident measurements of the two beams will restore the fringes behind a double slit. (See [3] and references therein). Usually, they entail far field point-like detection of the idler photons, while the signal beam is scanned horizontally. This is known as quantum erasure, but is also referred to by experimentalists as induced coherence. Quantum erasure implies that path information is erased when just a small subset of idler photons are detectable. Supposedly, the whole information would require the detection of all photons. Yet, fringes are produced only by the coincident subset on the signal path, which has well-defined properties, due to its EPR state. Consequently, induced coherence is more appealing as an interpretive concept, even though the formalism of quantum erasure has its own advantages.

Induced coherence is very important for the interpretation of quantum mechanics, because of the questions that it raises. Point-like measurements of the far field of the idler photons select a coincident subset of the signal photons with similar spatial properties. This can solve the problem of divergence and improve fringe visibility. However, these measurements do not have any obvious effects on the statistics of emission. Accordingly, they should not be able to overcome the known lack of temporal coherence, specific to chaotic beams. If so, what can explain the coherent build-up of fringes that is obviously happening? And if the preconditions for first-order interference are not met, are we dealing with a different phenomenon?

A good way to test for first-order interference is to close one slit. Normally, this should destroy the interference process and induce the projection of a diffraction pattern. Yet, coincident detection of idler photons and signal photons going through a single slit produces interference fringes of high visibility on the path of the signal [4]. This can be explained in terms of interference of the bi-photon amplitudes [5], and is also known as non-local double-slit interference. It also leads to a surprising hypothesis about the set-up with two slits. Coincident measurement of the idler beam may also define the trajectories of entangled signal photons. The latter can only go through one slit at a time, but they must also experience real-time bi-photon interactions after passing through. Ergo, it is also likely that interference distributions emerge from each slit and project constructively onto the plane of the detector. According to this description, quantum erasure must mimic first-order interference, without producing it, at least in some cases. But how are we to test this hypothesis?

If interference fringes are produced as superimposed independent sets, then it should be possible to separate each component. For example, the slits could be marked by opposite circular polarizers with orthogonal fast axes. This would automatically eliminate the possibility of Young interference behind the slits. On the other hand, if the distributions are produced by non-local effects between signal and idler photons, they should merely become shifted by half a cycle from each other. Separation can be achieved via coincident detection with the idler, by filtering the latter with a linear polarizer. When the axis of the linear polarizer of the idler is parallel to the fast axis of one marker on the path of the signal, it should reveal a set of fringes for coincident signal detection events. An orthogonal measurement of the idler should reveal the shifted fringes from the other slit, which would be called anti-fringes. Measurements for intermediate polarization states of the idler would enable again the detection of coincident signal photons that emerge from both slits. This would cause an overlap of fringes and anti-fringes. For the diagonal setting, the overlap would be perfect and the fringe pattern should wash out completely.

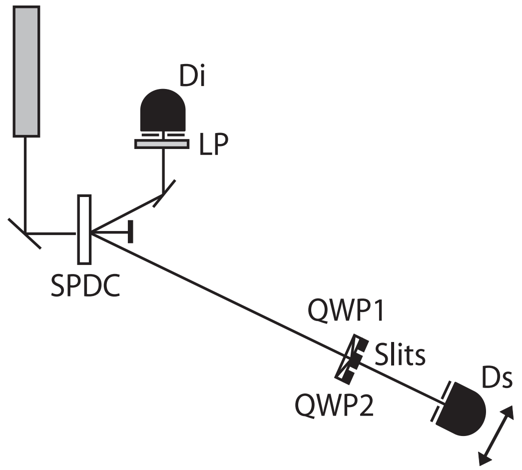

FIG. 1: Basic set-up of the proposed experiment. Quarter-wave plates QWP1 and QWP2 have orthogonal fast axes and induce circular polarization in opposite directions on each path. The idler photons must be detected at Di before the signal photons can reach either slit. LP is a linear polarizer. Lenses and filters that may be required, as well as the coincidence circuit, are not shown.

The experiment proposed above has been already performed by Walborn and collaborators [6]. Their results are in perfect agreement with the presented description. However, the authors have shown that the formalism of quantum erasure explains the outcomes just as well. Thus, the experiment did not provide enough information for a clear distinction between competing interpretations. Either quantum erasure mimics first-order interference, or it actually produces it by overriding the physical parameters of the experiment via negative temporal effects. As a consequence, a further refinement of this test is necessary. The hypothesis presented above implies that fringes are due to non-local signal-idler interactions in real time. The passage of a signal photon through a slit must be treated as a perturbative measurement. Thus, clear fringe visibility requires the possibility of interaction between entangled photons behind the slits and prior to detection. If the idler were detected before the signal reached the slits, it would define its path without being able to interact with it subsequently. Ergo, fringe visibility should diminish dramatically. On the other hand, if quantum erasure operates literally as commonly interpreted, the time of detection of the idler should not have any effect on the outcome. Fringes should persist at the same level of quality.

In light of the above, it would be highly instructive to repeat the experiment of Walborn *et al.* [6] with the following modification (FIG. 1). The set-up must be kept unchanged for the signal path. The idler beam must be reflected to the side, as close as possible to its source. A lens with short focal distance may be introduced as an option, in order to create far-field conditions before signal photons reach the slits. Idler photons must be detected with a point-like detector in the central part of the beam. It is imperative to ensure that idler photons are detected before the signal photons reach the double-slit. It is already well demonstrated that fringe visibility is high when the idler is detected after the passage through the slits by the signal, even if the idler is detected long after the signal. In fact, in the experiment of Walborn *et al.* fringes are more symmetrical for delayed detection, than for early detection. This could be an indication that non-local interactions happen all the way to the first detector, and the effect on the signal photons is more complete in the delayed erasure set-up. However, the authors of the experiment believe that a measurement artifact (such as k-vector filtering) could also explain the asymmetry of fringes during early detection [7]. As a corollary, the idler photons must be detected before the signal photons reach the slits, in order to remove any interpretive ambiguity about the real mechanism behind quantum erasure.

* Electronic address: g.mardari@rutgers.edu

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